An Estimation and Verification of Vessel Radar-Cross-Sections for HF Surface Wave Radar

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Abstract— **The radar cross sections (RCS) of both small and large ships for High Frequency Surface Wave Radar (HFSWR) were studied by using Numerical Electromagnetics Code [4] and by using measurements from a HFSWR system at Cape Race, Newfoundland, Canada. The results of the study indicate that Teleost, a 2405-ton Canadian Coast Guard ship, and large cargo-container vessels (~36000 ton) have comparable RCS values at 3.1 and 4.1 MHz. This was verified by comparing Teleost signals with the reflections of seven cargo-container vessels identified during an operational evaluation of the HFSWR. The conclusion of the study is that Teleost and the large cargo-container vessels have an angle-averaged RCS of ~40dBm^2, while small vessels (~1000 tons) could reasonably be characterized by an angle-averaged RCS of ~30 dBm^2, in the lower end of the HF band (3-5 MHz).**

I. INTRODUCTION

One of the parameters in the radar equation that determines the radar performance is the radar cross section (RCS) of the target. High Frequency Surface Wave Radar (HFSWR) in a coastal surveillance role is designed mainly to detect ships over a sea surface. The radar cross section of the ship to be detected is therefore a critical parameter in the design of the HFSWR. Little is discussed in the open literature about the RCS of ships of various sizes and at different aspects for HFSWR, although the free-space radar cross section of a vessel in m^2 is sometimes approximated by

$$\sigma = 52\ f^{1/2}\ D^{3/2} \qquad (1)$$

where D is the full-load displacement of the vessel in kiloton and f is the radar frequency in MHz. The above empirical formula was derived from measurements made at X, S and L bands [1], and extended as a rough approximation to the HF band for HFSWR [2]. The formula, however, does not consider the significance of the effect of vessel height on vessel RCS.

Vertical-polarized transmission is used in HFSWR. The vessels of interest could have masts that are as high as 25 m. This means that in the HF band, the vessel RCS is in the Rayleigh and resonance regions [3]. In the Rayleigh region, the target RCS decreases rapidly with radar wavelength. In the resonance region, the target RCS fluctuates within a confined range with radar wavelength. The height of the vessel is therefore significant in determining the RCS for HFSWR.

In this paper, we present the results of a study of the RCS for small and large commercial vessels in the lower end of the HF band (3-5 MHz) using Numerical Electromagnetics Code (NEC) [4] and trial data from the HFSWR at Cape Race, Newfoundland. Here small vessels refer to those with displacements of ~1000 ton and large vessels refer to cargo-container ships with displacements of several tens of kilotons. These are two groups of ships routinely tracked by the HFSWR.

A generic small vessel is modeled after Teleost, a 2405-ton Canadian coast guard ship (CCGS). Teleost was used as a control target in a trial to provide measurements of the target signal at selected aspects. The ship sailed outbound and then inbound along the boresight to provide measurements at stern-on and bow-on aspects. At a close range, the ship also turned to provide measurements at every 30 degrees. The structure of the ship was modeled using a simple wire-grid model and the RCS of the ship was calculated using NEC. The calculated RCS was then compared with the RCS estimated from the measurements using the first-order sea echo in a fully developed sea [5, 6]. A favourable comparison led to confidence in the model. This model was then scaled down to provide the radar cross sections of the smaller ships.

A second trial at Cape Race was carried out during an operational evaluation of the radar from which the identities and positions of seven cargo-container vessels were established. This allowed us to relate the RCS of Teleost to those of large vessels. One of the large vessels was also modeled and its RCS calculated.

II. RADAR CROSS SECTIONS OF SMALL VESSELS

Figure 1 shows a photograph of Teleost and a simple wire grid model for the ship. The length of the ship is 63 m and the breadth is 14.2 m. To calculate the RCS of the model, the grid is reflected in the horizontal plane, and then NEC calculates the cross section of the entire structure. Hence, the results here refer everywhere to the "net" RCS, not to the equivalent free-space RCS which is made 12 dB smaller in order to account for the gains of antennas operating over a conducting surface [7]. To test the effect of grid spacing, two Teleost models were generated, first with 3.5-m grid

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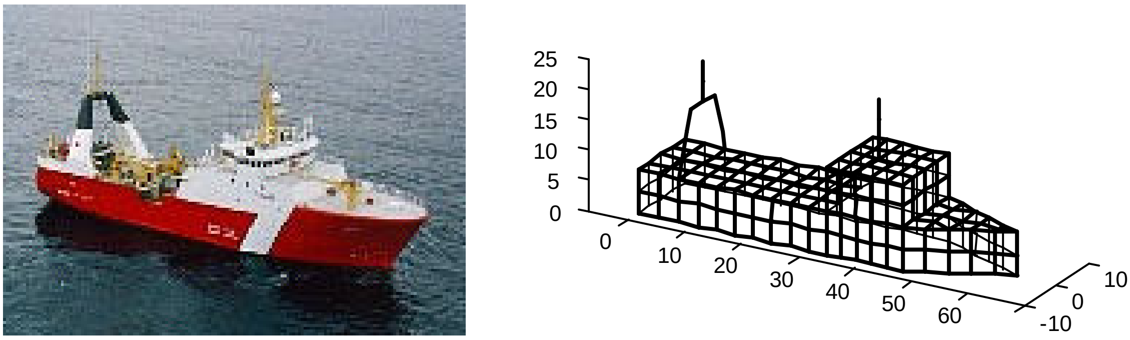

Figure 1. CCGS Teleost. Left: photograph. Right: wire grid model used to calculate RCS. Grid spacing=3.5 m. Wire radius=0.5 m.

spacing and 0.5-m wire radius and then with 2.2-m grid spacing and 0.3-m wire radius. Including the images, the numbers of wire segments are 814 and 1846, respectively in the two models. Because of the larger number of segments in the second model, the execution time to complete the RCS calculation using the second model is about 12 times that calculation using the first model. The two models give RCS estimates that differ by <20% (0.8 dB), so we are confident that the first model with the coarser grid spacing is adequate. The aspect dependence of the modeled RCS of Teleost at 3.1 and 4.1 MHz is shown in Figure 2 where Φ=0° indicates bow-on incidence.

The Cape Race HFSWR was calibrated using the strength of the Bragg lines in the sea-clutter spectrum. References [5, 6] show that, for a fully developed sea, the Bragg-line scattering coefficient, defined as the effective echoing cross section per unit area of sea surface, is –20 dB. For a patch area *A*, the radar cross section is given by

$$\sigma_{Bragg} = 0.010\ A \tag{2}$$

Two separate sets of data where the wind had been blowing at 20-30 knots for several hours and the significant wave heights ranged from 4 to 6 m gave the same radar calibration, and this calibration confirmed that the RCS of Teleost at Φ=180° (i.e. stern-on) has 41 dBm^2 at 4.1 MHz. In addition, Teleost sailed in a 12-sided loop so we could monitor the variation of RCS with aspect angle. The dots in the bottom of Figure 2 show the strength of the reflected signal measured in 30° steps and estimated using the first-order sea echo. (We assume left-right symmetry, so data from -180°<Φ<0° have been plotted at -Φ.) The good agreement between the dots and the numerical model shows that NEC also reproduced the dependence of the RCS on the aspect angle Φ.

At 3.1 MHz, a Bragg-line calibration gave an end-on RCS of 44 dBm^2 while NEC predicted only 40 dBm^2. It is harder to justify the simple relation in (2) since the sea is likely not fully developed at 3.1 MHz where the ocean waves responsible for the Bragg lines have a wavelength of 49 m. In any event, it would not change our conclusions, since this

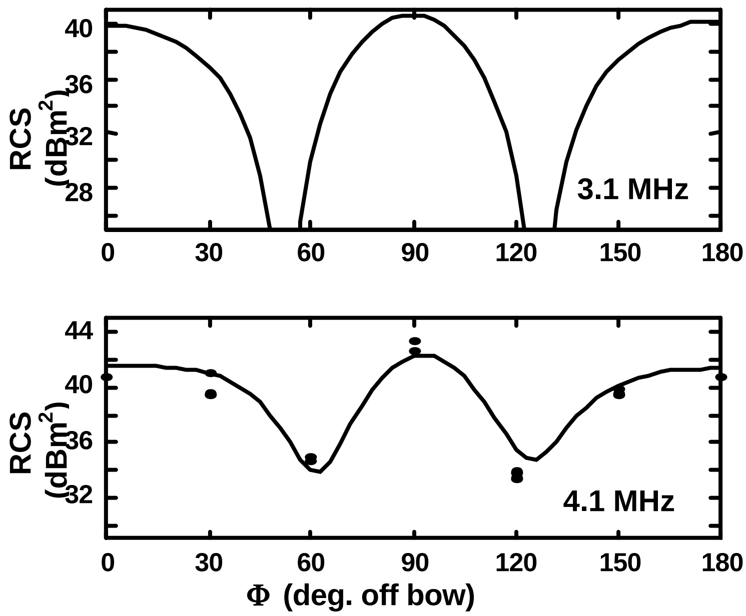

Figure 2. Numerical estimates of Teleost's RCS at 3.1 MHz (top) and 4.1 MHz (bottom). The dots show the measured angular dependence normalized to match the calculated results. The measured value at 4.1 MHz and ϕ=180° is 41 dBm^2.

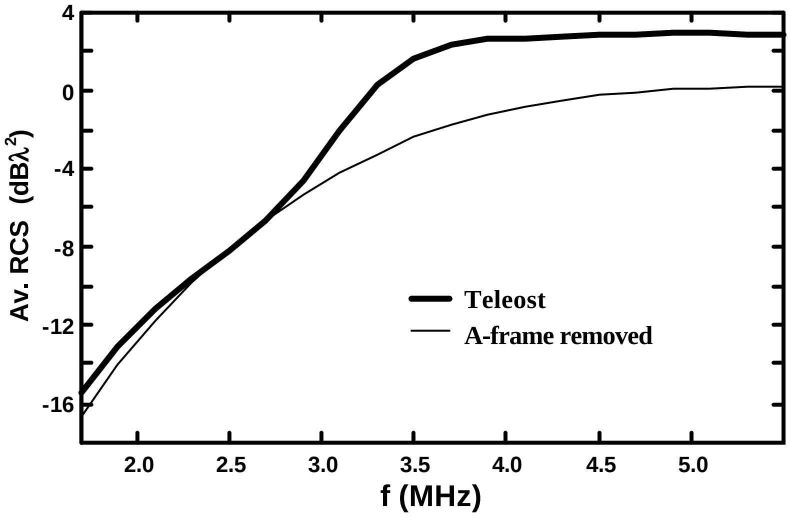

Figure 3. The aspect-angle-averaged RCS for the wire-grid model of Teleost and the model with the A-frame near the stern removed.

difference would change the estimated cross sections by at most 4 dB.

Analysis of the model also shows that an angle-averaged RCS of Teleost is 38 dBm^2 at 3.1 MHz and 40 dBm^2 at 4.1 MHz (2 and 1 dB below the end-on RCS respectively).

To determine the RCS of smaller vessels, the first step was to calculate the RCS of Teleost at frequencies from 1.8 to 5.5 MHz. Figure 3 shows the aspect-averaged RCS of Teleost and also the RCS for the same model, but with the A-frame near the stern removed. Examination of several models showed that the A-frame and its mast had a large effect on the RCS near 4.1 MHz, but that the mast above the bridge had a much smaller influence. It is to be expected that all ships will have one mast and an elevated bridge, but the stern A-frame is likely less common, so to model small ships it was removed. Note that the RCS in Figure 3 is normalized to $(\text{wavelength})^2$, not m^2.

The results for the Teleost model are extended as an approximation to smaller vessels by using the fact that if the linear dimensions of a structure are multiplied by a factor α, and the wavelength is also multiplied by α (i.e. the frequency is divided by α), then the ratio σ/λ^2 does not change. The model of a tonnage-D ship is obtained by scaling the Teleost model by a factor

$$\alpha = \left(\frac{D}{D_0}\right)^{1/3} \tag{3}$$

where D_0 = 2405 tons is Teleost's gross tonnage. Then $\sigma(D,f)$, the angle-averaged RCS of the tonnage-D ship at frequency f, is related to the RCS of Teleost without the A-frame by

$$\sigma(D, f) = \sigma(\alpha^3 D_0,\, f) = \alpha^2 \sigma_0(\alpha f) \tag{4}$$

Figure 4 shows the angle-averaged RCS of the smaller ship modeled after Teleost without the A-frame, at the radar frequencies of 3.1 and 4.1 MHz.

Figure 4 shows that an estimate of the RCS of the 1000-ton vessel is 29 dBm^2 at 3.1 MHz and 32 dBm^2 at 4.1 MHz. These

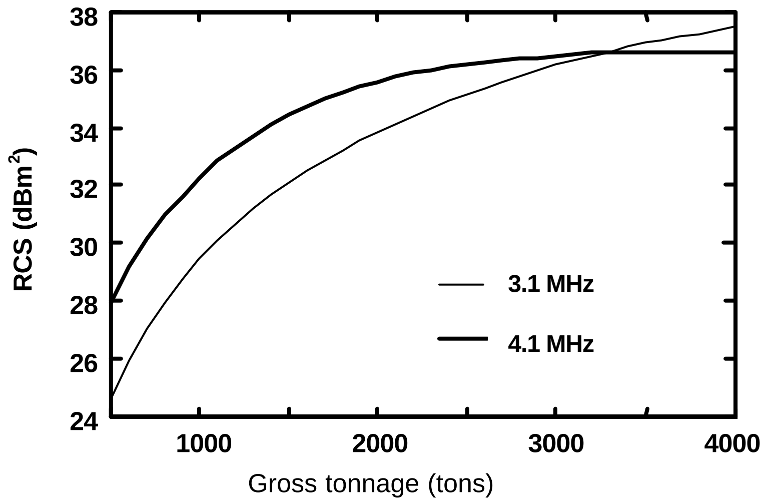

Figure 4. The angle-averaged RCS as a function of tonnage for ships with Teleost's shape, but with the A-frame removed.

values stand 11 and 9 dB respectively below the end-on RCS of Teleost shown in Figure 2. With the accuracy of approximations used here, this could be rounded to 10 dB, so we use an angle-averaged RCS of a 1000-ton vessel that is ~10 dB below the end-on RCS measured during the controlled-ship trial with Teleost in January 2002. To derive results for a 500-ton vessel, the angle-averaged RCS should be reduced to 25 dBm^2 at 3.1 MHz and 28 dBm^2 at 4.1 MHz.

III. RADAR CROSS SECTIONS OF LARGE VESSELS

Ground-truth flights on 8 and 9 Feb. 2002 established the identities of several large vessels that were tracked by the radar and recorded in radar data. These included Bonn Express (35915 ton, 236m long, 32.2m beam), Hong Kong Express (36606 ton, 245m long, 32.3m beam), OOCL Canada (33662 ton, 216m long, 32.2m beam), Atlantic Cartier (30731 ton, 250m long, 32.3m beam), Vancouver Spirit (63709 ton, 244m long, 42m beam), Marit Maersk (4300 TEU, 244m long, 32.3m beam), and Maria Gorthon (11491 ton, 156m long, 21.9m beam). Figure 5 displays the observed signal levels from the 7 vessels and compares to the 3.1- and 4.1-MHz signals measured from Teleost in an end-on orientation. The Teleost signals have been extrapolated from the ranges where measurements were made (360-400 km at 3.1 MHz and 150-240 km at 4.1 MHz) to other ranges using the known attenuation of electromagnetic surface waves over a stormy ocean. The data show that reflections from 7 vessels, ranging from 150-m length and 11000 tons to 294 m and 64000 tons, are not significantly stronger than the end-on reflections of Teleost.

We investigated this using NEC to calculate the RCS of a wire-grid model of a 36000-gross-ton container ship ("Bonn Express"), which happened to travel across the radar beams during the ground-truth flights. This is a typical container vessel: it is 236 m long, has a beam of 32 m and estimate that the top of the container stack on the deck is 20 m above the waterline, and the bridge/funnel are modeled as 30 m high. Figure 6 shows the wire grid generated for this ship. The grid spacing in the model is 7 m and the wire radius is 1 m. The complete model, including the image, has 1794 wire segments.

The NEC calculations of the RCS of this model are displayed in Figure 7. Note that at most aspect angles, the RCS of a large container ship is not much greater than the RCS of Teleost, in spite of the fact that the container ship has 15 times the gross tonnage of Teleost. The angle-averaged cross sections for Bonn Express are 41 dBm^2 at 3.1 MHz and 43 dBm^2 at 4.1 MHz, which are only 3 dB greater than those of Teleost. The large cross section of Teleost is due to the contribution from the front and after masts (24 m), which are higher than the deck height of Bonn Express, but lower than the bridge/funnel height of the larger ship.

Figure 7 also shows that near broadside (Φ=90°), there is a large peak in the RCS of the large vessel (48 dBm^2 at 3.1 MHz and 52 dBm^2 at 4.1 MHz). This explains the observation that occasionally vessels traveling tangentially are seen at very far ranges. A note of caution: Figure 7 shows the RCS

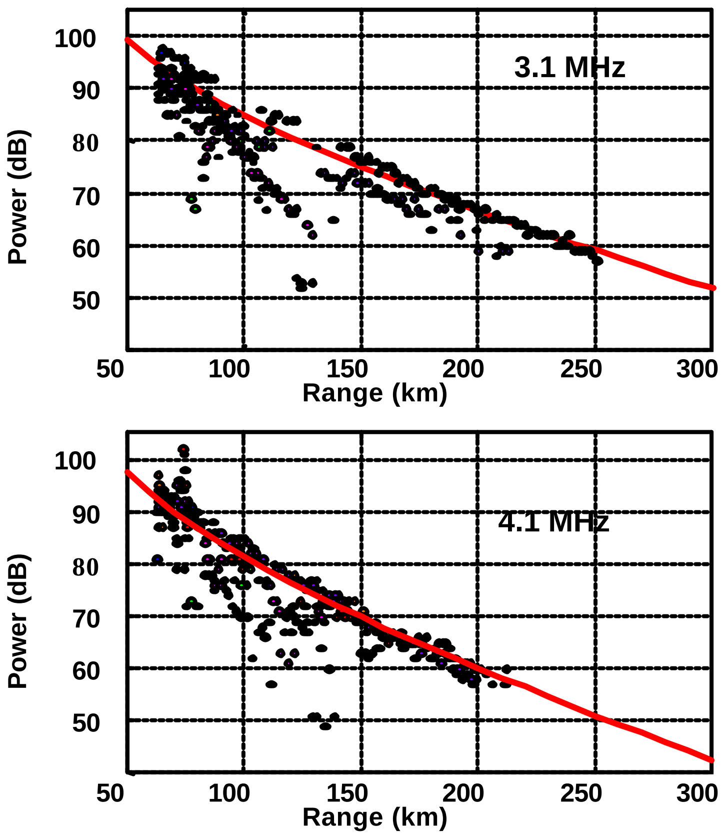

Figure 5. The strengths of the signals from seven known cargo vessels identified by ground-truth flights on 8 and 9 Feb. 2002. The vessels ranged in size from 11000 to 65000 tons and from 150 m length to 294 m. The solid red line shows the measured strength of reflections from Teleost in an end-on orientation.

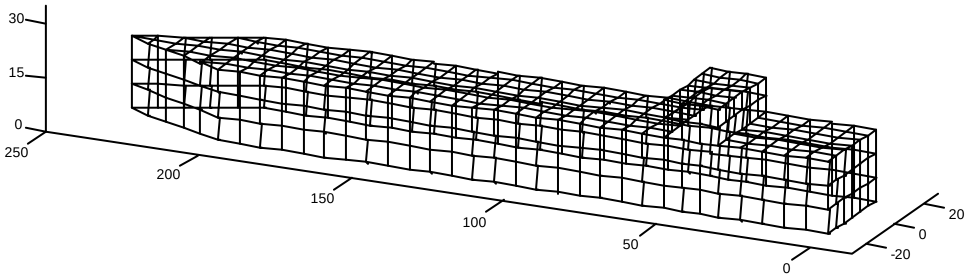

Figure 6. Wire grid model of Bonn Express used in the NEC calculation of the RCS. The grid spacing is 7 m with 1-m wire radius. The complete model, including the z<0 part, has 1794 segments.

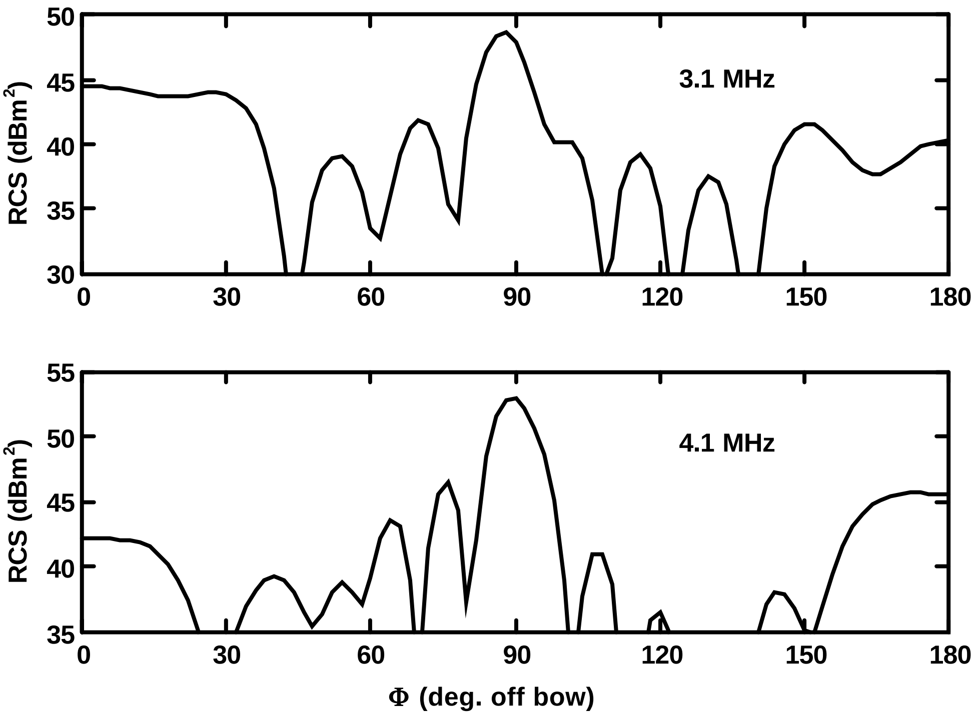

Figure 7. NEC estimate of the RCS of Bonn Express, a typical container ship (36000 gross tons). The angle-averaged cross sections are 41 dBm^2 at 3.1 MHz and 43 dBm^2 at 4.1 MHz. The dimensions of Bonn Express: length=236 m, beam=32 m, main deck height=~20 m, bridge/funnel height=~30 m

dropping to very low values away from 90°. This is partly a result of the simple wire-grid model. A real ship would be expected to show nulls in the cross section, but probably not as deep as shown in the figure. Similarly, the cross section at 4.1 MHz between 120° and 150° would probably be higher in a model that includes more details of the vessel's superstructure.

IV. Summary

In modeling and measuring the vessel RCS, we have determined that Teleost, a medium sized coast guard vessel, and large cargo-container vessels have about the same RCS, and this RCS is ~40 dBm^2 when it is averaged over all aspects. The similar RCS for a 1000-ton small vessel is ~30 dBm^2. The computed RCS also shows an angular variation with peaks and nulls, which were partially verified with measurements from Teleost and could further be verified with measurements from Bonn Express that traveled across the radar beams during the ground truth flights.

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